Effect of Broken Clouds on Satellite-Based Columnar Water Vapor Retrieval

Petr Chylek, Christoph Borel, Anthony B. Davis, Steven Bender, John Augustine, and Gary Hodges

***Abstract*—We investigate the effect of broken clouds on the satellite-based retrieval of columnar water vapor using a near-infrared radiance ratio technique. A typical difference between the retrieval using only pixels directly illuminated by the sun and pixels with mixed illumination containing direct sunlight as well as cloud shadows is found to be within 3%.**

***Index Terms*—Broken clouds, remote sensing, satellite, water vapor.**

I. Introduction

WATER vapor is one of the most important variable components of the atmosphere. It plays a major role in the redistribution of water and energy within the climate system. In remote sensing, the total amount of water vapor in an atmospheric column, i.e., columnar water vapor (CWV), is needed for atmospheric corrections, especially for thermal infrared observations. Commonly used satellite columnar water vapor retrieval is based on the measurement of solar near-infrared radiation reflected by the surface toward the satellite instrument. Such radiation is partially absorbed by the water vapor (predominantly within the spectral region of the water vapor absorption bands) during its two-way passage through the atmosphere. By comparing the satellite-observed radiances with those calculated from the radiative transfer codes for properly selected model atmospheres, we can deduce the amount of water vapor along the path.

The radiative transfer models used in the retrieval are usually one-dimensional (1-D) codes that consider the height to be the only direction along which the atmosphere is allowed to vary. In other words, the atmosphere is considered to be vertically stratified but horizontally homogeneous. For the most part, however, this assumption is rarely satisfied. One of the common cases of a horizontally nonhomogeneous atmosphere happens when there is a broken cloud layer.

The surface illumination under broken-cloud conditions varies significantly in the amount and type of the solar radiation. The surface incident solar flux can often vary by a factor of ten on the boundary between the directly illuminated ground and cloud shadows. The character of the illumination also varies between the monodirectional solar beam and completely diffuse solar radiation resulting from molecular, aerosol, and cloud scattering. The spectral composition of direct and diffuse solar radiation differs slightly due to the spectral dependence of atmospheric absorption and scattering. To describe properly the surface illumination and the outgoing top-of-atmosphere (TOA) radiances under the broken-cloud conditions, three-dimensional (3-D) radiative transfer codes should be used. However, such codes would require a very detailed input concerning the state of atmosphere and clouds, as well as a large amount of computer time. Consequently, at present the 3-D codes are not being used in satellite-based operational retrievals. Therefore, a question arises: what error, if any, is introduced by using the 1-D radiative transfer codes under broken clouds conditions? The answer to this question depends on the parameter we are trying to retrieve from remote sensing. In this letter, we investigate the effect of broken clouds on the columnar water vapor retrieval using the continuum interpolation band ratio method.

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II. Columnar Water Vapor Retrieval Algorithm

Most methods used for satellite-based columnar water vapor retrieval use as an input measurements of TOA outgoing radiances within, and outside, selected water vapor absorption bands. The ratio of the measured radiances is then related to the amount of water vapor along the path. There are several variations of this basic principle including the differential absorption method [1], the narrowband and wideband ratio [2], the atmospheric precorrected differential absorption (APDA) [3], and the continuum interpolation band ratio (CIBR) methods [4], [5].

The CIBR method reduces errors due to the variability of spectral surface reflectivity in the region of the spectral bands used for the retrieval. It is based on the CIBR index defined as (we are adopting here the "Multispectral Thermal Imager (MTI)" band notation, which is explained in the following section)

$$\mathrm{CIBR} = \frac{F}{aE + bG}$$

where F is a satellite-observed radiance in the channel within a water vapor absorption band (Fig. 1), and E and G are radiances in nearby reference channels located on each side of the absorption band F. The coefficients a and b determine the linear combination of the two reference channels (E and G) used. They are usually weighted by the spectral distance between the absorbing and the reference channels.

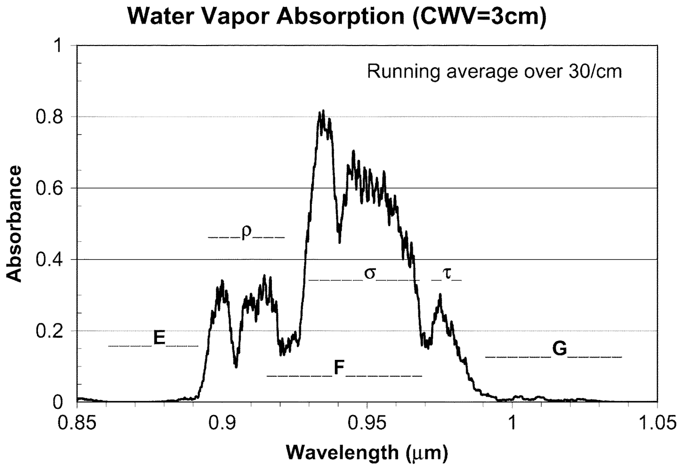

Fig. 1. Absorbance of 3-cm CWV in the 0.85–1.05-μm spectral range. Three major water vapor absorption bands (ρ, σ, and τ) are located in this region [6]. The positions and widths of MTI bands E, F, and G are indicated. Calculation performed using the MODTRAN 4.0 code with midlatitude summer model atmosphere.

III. Department of Energy MTI

In our columnar water vapor retrieval, we will use the imagery produced by MTI, a Department of Energy (DOE) technology demonstration satellite. The MTI is a pushbroom multispectral satellite instrument [7], [8] with 15 spectral bands from visible to thermal infrared wavelengths. It was launched in March 2000 into a sun-synchronous orbit at approximately 575-km altitude. MTI's pixels are 5 m $\times$ 5 m in the visible and 20 m $\times$ 20 m in the infrared region; its swath width is around 12 km. Three MTI bands (E, F, and G with wavelengths centered at 874, 940, and 1015 nm) are used with the CIBR method of the columnar water vapor retrieval (Fig. 1).

The MTI's small pixel size eliminates most errors in retrieval due to unresolved subpixel size cloudiness. In addition to clear-sky images, partially cloudy scenes can be used for retrievals. For the purpose of atmospheric corrections, MTI retrieves both the CWV and aerosol optical depth. The accuracy [root-mean-square error (RMSE)] of the MTI CWV retrieval is between 11% and 12% for CWV amounts above 1 g/cm^2 [9], while the RMSE of the aerosol optical thickness retrieval is 0.03 in aerosol optical depth [10], [11].

IV. Effect of Broken Clouds on Surface Illumination

To demonstrate the effect of broken clouds on surface illumination, we will use two 12-h time intervals of surface measurements of direct, diffuse, and total downwelling solar radiation from the SURFRAD [12] station at Table Mountain near Boulder, CO.

The direct solar radiation is measured on the plane perpendicular to the direction to the sun, while the total downwelling radiation is measured on the horizontal plane. It is the total downwelling solar flux that illuminated the targets observed by satellite instruments. On July 10, clear sky conditions existed. For a few hours around local noon, the total downwelling solar flux is larger than the direct flux, due to the contribution from the diffuse radiation scattered by air molecules and aerosol particles

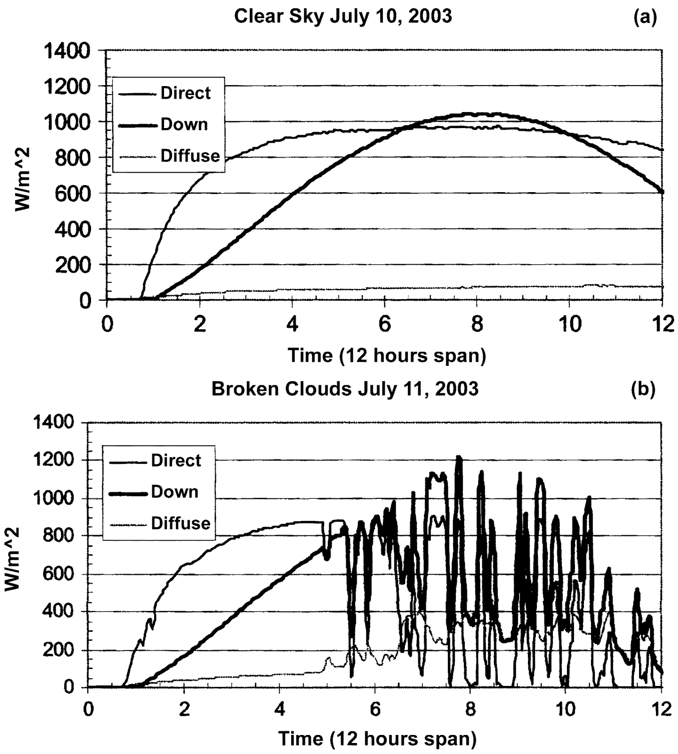

Fig. 2. Twelve-hour records of direct, downwelling, and diffused solar radiation on (a) a clear sky day and (b) a partially cloudy day (broken cloud field) at Table Mountain near Boulder, CO.

[Fig. 2(a)]. The maximum downwelling flux during the clear day is between 1030–1040 W/m^2.

On July 11 [Fig. 2(b)], we have clear sky conditions in early morning with a broken cloud field developing later during the day. The direct solar flux is reduced to almost zero when a cloud is in the path between the sun and the instrument detector. Around midday, the total downwelling solar flux is at times reduced from typical values of just over 1000 W/m^2 to about 200–400 W/m^2 by intervening clouds. When the cloud does not block the direct normal beam, the total downwelling flux is enhanced by the positive contribution of radiation reflected by surrounding clouds. Under these conditions, the total downwelling flux can be greater than if clear sky conditions existed. We see this in Fig. 2(b), where the maximum values of the total downwelling flux under broken clouds conditions reaches 1200 W/m^2, while the maximum total downwelling flux during the clear sky day (July 10) is between 1030–1040 W/m^2. In addition, the spectral composition of solar flux will be slightly different on clear and cloudy days, due to spectral dependence of the absorption and scattering by atmospheric gases and aerosols.

V. CWV Retrieval Using Pixels With Direct and/or Diffuse Solar Illumination

To determine the effect a broken cloud field has on the columnar water vapor retrieval, we have analyzed 32 partially cloudy cases of the CWV retrieval. The images of the NASA Stennis Space Center (30°22′ N, 89°37″ W, 20 m above mean sea level) were obtained with the DOE MTI within the time period from June 2000 to June 2002. Fig. 3 shows an example of the Stennis site (area of about 10 km $\times$ 10 km)

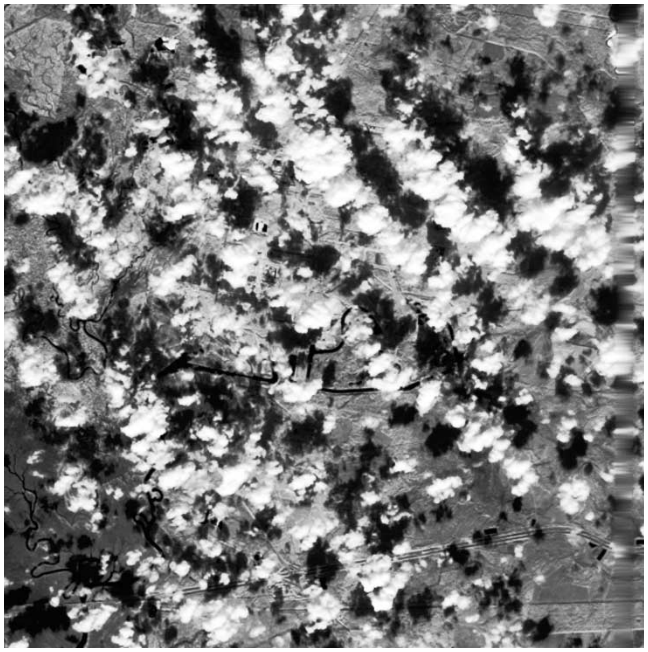

Fig. 3. One of the MTI images used for columnar water vapor (CWV) retrieval shows the distribution of clouds and their shadows. A threshold-based classification suggests about 13% and 15% of the area covered by clouds and cloud shadows, respectively.

with a 20 m $\times$ 20 m pixel size resolution. We readily recognize regions covered by clouds and cloud shadows and those areas illuminated directly by the sun. The threshold-based classification suggests about 13% of the area covered by clouds and about 15% by cloud shadows. Typical linear dimensions of most of the clouds are in the 50–500-m range. The CWV varies between 2.5 g/cm^2 for clear areas and 1.75 g/cm^2 for CWV above the clouds.

TABLE I
AMOUNT OF COLUMNAR WATER VAPOR (GRAMS PER SQUARE CENTIMETER) RETRIEVED FROM AREAS WITH DIFFERENT KINDS OF ILLUMINATION. THE COLUMNS "Shadow," "Sunlight," AND "Cloud" MEAN REGIONS COMPLETELY OCCUPIED BY A CLOUD SHADOW, DIRECT SUNLIGHT, AND A CLOUD, RESPECTIVELY. THE COLUMN "Shadow and Sunlight" DESIGNATES THE AREA WITH THE MIXED ILLUMINATION WHERE A PART OF AN AREA IS IN A CLOUD SHADOW AND A PART IN DIRECT SUNLIGHT. THE COLUMN "Cl, Sh, Sun" DESIGNATES AREAS THAT INCLUDE CLOUDS, CLOUD SHADOWS, AND DIRECT SUNLIGHT

Case No	Image ID	Shadow	Sunlight	Shadow and Sunlight	Clouds	Cl,Sh,Sun
1	107921-1	2.68	2.66	2.69	2.06	2.51
2	107922-1	2.43	2.96	2.85	2.02	2.38
3	107911-1	2.31	2.58	2.43	1.81	2.18
4	107910-1	2.48	2.45	2.45	1.69	2.19
5	107910-2	2.53	2.57	2.45	1.57	2.15
6	107910-3	2.52	2.56	2.54	1.6	1.75
7	107910-4	2.38	2.6	2.55	1.69	2.34
8	107910-5	2.51	2.53	2.55	1.63	2.02
9	107910-6	2.4	2.46	2.43	1.75	2.25
10	107910-7	2.45	2.46	2.51	1.68	2.01
11	107910-8	2.52	2.47	2.53	1.68	2.19
12	107910-9	2.39	2.46	2.51	1.61	1.75
13	107910-10	2.45	2.48	2.41	1.71	2.06
14	107910-11	2.47	2.47	2.48	1.59	2.03
15	107930-1	2.38	2.46	2.46	2.15	2.41
16	107930-2	2.24	2.44	2.33	2.11	2.23
17	102093-1	1.44	1.45	1.44	0.74	1.19
18	102094-1	1.29	1.47	1.36	0.81	1.11
19	026247-1	4.52	5	4.92	2.94	3.96
20	026240-1	3.82	3.96	3.95	2.34	3.38
21	023277-1	3.96	5.03	4.61	2.42	4.55
22	023277-2	4.06	5	4.74	2.78	3.9
23	023284-1	3.43	4.13	3.72	2.05	2.68
24	023284-2	4.22	5.16	4.72	3.41	4.25
25	022193-1	3.45	3.77	3.61	2.32	2.93
26	022193-2	3.43	3.78	3.73	1.54	3.04
27	022200-1	3.27	4.13	3.68	1.88	3.47
28	022200-2	3.61	4.2	4.01	2.07	3.3
29	017826-1	2.24	2.4	2.31	0.27	1.46
30	017826-2	2.5	2.56	2.53	0.32	1.02
31	017819-1	3.17	3.15	3.15	0.32	1.89
32	017819-2	3.23	2.75	2.62	0.49	1.07

To determine the effect of varying solar illumination of the surface on the columnar water vapor retrieval, we chose areas that are: 1) located entirely in direct sunlight; 2) located entirely in shaded regions; and 3) a combination of the two. The amount of CWV retrieved from 32 studied cases is listed in Table I. To demonstrate the effect of subpixel size cloud contamination (for cases of instruments with larger pixel sizes) we also retrieve the CWV from regions containing a fraction of clouds (column 7 in Table I) and the amount of water vapor above the clouds (column 6 in Table I). The CWV retrieved from areas shaded by clouds (Table I, column 3) is generally lower than CWV retrieved from the areas with direct sunlight (Table I, column 3). A careful examination of the MTI radiometric calibration at very low radiances suggests that the lower CWV values retrieved from shaded area (low radiances) cannot be a result of the radiometric calibration error.

The radiation measurements (Fig. 2) show that on clear sky days, the amount of diffuse solar radiation stays below 100 W/m^2, while on days with broken cloud fields, the diffuse flux increases up to 400 W/m^2. This increase in diffuse radiation is primarily due to the multiple-scattered radiation transmitted through the cloud. The spectral composition of this radiation is affected by spectrally dependent absorption and reflection of solar radiation by cloud droplets. The diffused radiation scattered by air molecules and aerosols can have both the longer and the shorter path (with respect to the direct sunlight) through the atmosphere toward the considered target region. The positive and negative path differences through the atmosphere suggest the possibility of the both the higher and the lower amount of the CWV determined from the cloud shadow regions (compared to the CWV determined form regions illuminated by direct sunlight). Consequently, the differences between CWV determined from shaded and sunny regions depend on the pathlength of the radiation scattered outside the cloud, on the ratio of the incident flux scattered by a cloud to that scattered by the aerosols and molecular atmosphere, and on the surface reflectivity.

A cloud mask is being generally used to eliminate the cloudy pixels from the CWV retrievals. The remaining areas are usually a mixture of regions with direct sunlight and cloud shadows. The retrieved CWV from such mixed regions (Table I, column 5) are on average about 3% lower (Fig. 4) when compared to the CWV retrieved from only directly illuminated regions. Considering a typical accuracy of the CWV satellite-based retrievals [9] to be around 10%, the additional error of 3% due to cloud shadows will increase the total RMSE only to RMSE $= \sqrt{0.10^2 + 0.03^2} = 0.104$. Thus, the effect of

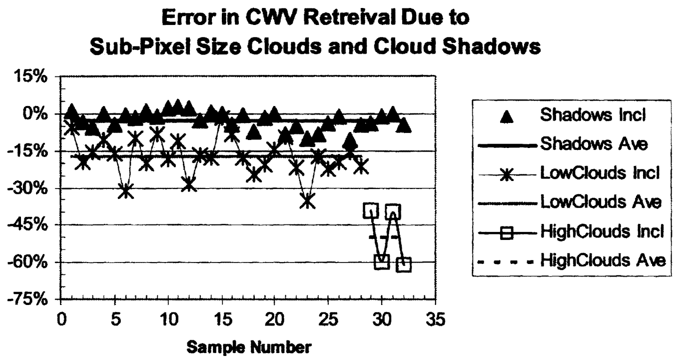

Fig. 4. Retrieved CWV amounts from regions that include pixels in cloud shadows as well as pixels directly illuminated by sunlight is only slightly underestimated (on average by 3%) compared to CWV determined from regions completely in sunlight, suggesting that 3-D aspects of the radiation field can be neglected for CWV retrieval as long as the cloud-contaminated pixels are excluded. Inclusion of pixels containing clouds in retrieval leads to a significant error. A subpixel low cloud contamination produced an average error of 17%, while the high cloud contamination led to 50% underestimate of the CWV.

the broken cloud field on the accuracy of the CWV retrieval is not significant as long as the clouds themselves are excluded from the regions used for the retrieval.

Satellite instruments with a larger pixel size experience difficulties in identifying and eliminating pixels contaminated by subpixel size clouds. In the set of studied images, we find many clouds with a linear dimension of 20 m or less (identified through the MTI visible bands with the pixel size of 5 m). Subpixel size clouds will lead to a systematic underestimate of the CWV retrievals. The amount of the underestimate will depend on the fraction of area covered by clouds and on the height of the cloud top (the amount of water vapor above the cloud). Higher clouds will lead to a larger error than the lower ones. To simulate the effect of subpixel cloud contamination on the CWV retrieval, we have used the 500 m $\times$ 500 m areas that contained small clouds, cloud shadows, and direct sunlight. The retrieved CWV is shown in the last column of Table I. The CWV is underestimated on average by 17% for low-level subpixel size cloud contamination and by 50% for high clouds (Fig. 4). We conclude that subpixel size cloud contamination leads to a considerably larger error in the CWV retrieval than the inclusion of cloud shadows.

VI. Summary and Discussion

Broken clouds produce a complicated 3-D radiation field that causes high inhomogeneity in the illumination of the surface. The total downwelling flux reaching the surface varies significantly between the directly illuminated areas and areas in the shadows of clouds. At the same time, the character of the downwelling flux changes from one dominated by the direct solar radiation to a nearly pure diffuse one. One may expect that application of 1-D radiative transfer codes to this complicated 3-D radiation field might lead to significant errors in retrieved variables. We have investigated a specific case of columnar water vapor retrieval using the DOE MTI. We have found that in the majority cases, the effect of varying illumination of the surface due to broken clouds had a negligible effect on the CWV retrieval. The differences between the retrieved CWV using only directly illuminated pixels and mixture of pixels in direct sun and in cloud shadows were below 3%. On the other hand, the subpixel size clouds included in the retrieval lead to a significant underestimate of the CWV (17% for low-level clouds and 50% for high clouds). Our results were obtained mostly over the surface covered by green vegetation. In the case of surfaces with a very high reflectivity (desert areas) or a very low reflectivity (oceans), the effect of inclusion of clouds' shadows in the CWV retrieval may differ from the results presented here.

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